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SAND STABILISATION USING FOAMED BITUMEN

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SYNOPSIS

Stabilisation of poor quality materials with a foamed bitumen is a relatively new concept in Southern Africa. Main attractions of using a foamed binder are that a cold moist aggregate can be stabilised with a stiff premix grade bitumen (normally a 60/70 Pen) without the added cost of cutting back the binder with solvent or emulsification. In addition, curing of the mix is not required before compaction.

The shear strengths of a wide range of foam stabilised sand mixtures were evaluated in the laboratory, the main sand characteristics influencing shear strength being sand particle shape and filler content. Resilient moduli of a number of selected foam stabilised sand mixtures were determined using the repeated load indirect tensile procedure. Moduli were found to be sensitive to loading rate, applied stress level and temperature. Resilient moduli decreased with increase in stress level and reduction of loading rate.

Two full scale experiments were constructed with material stabilised in a drum mixer and mixed in situ. All stabilised sections showed a significant increase in shear strength with time and full laboratory strengths were reached six to ten months after construction.

By determining the effective moduli for the foam treated sand layer from both laboratory and field measurements, a structural design analysis was carried out using linear elastic theory to determine the required layer thickness for a given traffic level and wheel load. The design aim has been to add a minimum quantity of bitumen for adequate stability and to select the stabilised layer thickness to achieve acceptable vertical strains in the subgrade.

STABILISASIE VAN SAND DEUR DIE GEBRUIK VAN SKUIM-BITUMEN

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SAMEVATTING

'n Nuwe konsep in Suid Afrika is die stabilisasie van swak gehalte materiale deur die gebruik van skuim-bitumen. Die grootste aantrekkingskrag wat die gebruik van 'n skuim bindmiddel inhou is dat 'n koue, vogtige aggregaat met 'n harde (penetrasie) graad bitumen gestabiliseer kan word (gewoonlik 'n 60/70 pen) sonder om bykomende onkoste aan te gaan deur die byvoeging van 'n oplosmiddel of emulsifikasie. Boonop word nabehandeling van die mengsel nie voor verdigting vereis nie.

Die skuifvastheid van 'n wye reeks van skuim gestabiliseerde sand-mengsels is in die laboratorium bereken; die vernaamste sand-eienskappe wat skuifvastheid beinvloed synde die vorm van sanddeeltjies en vuller-inhoud. Die modulus (resilient) van 'n aantal uitgesoekte skuim-gestabiliseerde sandmengsels is vasgestel deur die "repeated load indirect tensile" prosedure. Daar is bevind dat die modulus sensitief is ten opsigte van die ladings tempo, die toegepaste spanningsvlak en temperatuur. Verende modulus verminder met die toename in die spanningsvlak en die spanningsvlak en die vermindering van die ladings tempo.

Twee volskaalse eksperimente is saamgestel met gestabiliseerde materiaal: een met materiaal in 'n drommenger gemeng en die ander in situ gemeng. Met die verloop van tyd het alle gestabiliseerde dele 'n betekenisvolle toename in skuifvastheid getoon en maksimum laboratorium sterkte is 6 - 10 maande na samestelling bereik.

Deur die vasstelling van die toepaslike modulus in die skuimbehandelde sandlaag van beide laboratorium en veldmate is 'n struktuurontwerp-ontleding uitgevoer waartydens 'n lineêr-elastiese teorie toegepas is om die verlangde laagte dikte vir 'n gegewe verkeersvlak en wiellading te bepaal. Die doelwit van die ontwerp was om die minimum hoeveelheid bitumen vir geskikte stabiliteit by te voeg en om die gestabiliseerde laag-dikte vas te stel om die vertikale spannings in die subgraad binne perke te hou.

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SAND STABILISATION USING FOAMED BITUMEN

1. INTRODUCTION

The method of applying a bitumen in the form of a foam for the stabilisation of poor quality materials was originally developed during the mid 1950's by Professor Csanyi of Iowa State University.[1] Controlled foaming of the bitumen was obtained by introducing steam into a hot paving grade bitumen. The low viscosity and volume expansion of the foam allowed intimate mixing with the cold moist aggregate without the need for cutting back the binder with solvent, or emulsification.

An alternative foaming system was later developed by Mobil Oil Australia in which cold water replaced steam injection and hence considerably simplified field control in practice.[2]

The basic system involves the introduction of cold water under controlled flow and pressure into a hot penetration grade bitumen. The foamed bitumen produced is then sprayed on to the curtain of aggregate via the nozzles of a spray bar. For stabilisation of material in situ the foamed bitumen is sprayed on to the aggregate thrown up by the tines of the rotovator. For a drum mixer the bitumen is added to the aggregate inside the drum (without the burners operating) and in the case of the batch mixer the foamed binder is added to the cold moist aggregate in the pugmill.

This paper presents an investigation in which the properties of a wide range of foam bitumen stabilised sands were evaluated in the laboratory and under full scale field conditions. The practicalities of constructing the sand stabilised layer are also discussed.

2. MATERIALS EVALUATION

The shear strengths of twenty one different foam bitumen stabilised sand mixtures were measured in the laboratory using the vane shear apparatus and Hveem stabilometer.

The laboratory preparation of the stabilised mixtures followed the procedure outlined by Bowering and Martin.[3] Foamed bitumen was mixed with the cold moist sand in a planetary mixer. Moisture content of the sand was 3-4 percent less than o.m.c. for maximum dry density. Compaction of the Hveem samples was carried out using the kneading compactor and vane shear samples were compacted in a CBR mould using Mod. AASHO compaction. Specimens were then oven cured for three days at 60°C prior to testing.

Sands evaluated covered a good cross section of fine aggregate characteristics, the main sand properties considered being gradation, particle shape and filler content. Poor correlations were obtained between grading parameters (fineness modulus, coefficient of uniformity) and shear strength, although in general well graded sands had higher stabilities. Maximum Hveem Resistance Value (for both before and after moisture vapour soak) and maximum vane shear strength are shown for each sand in Appendix 1. In all cases stabilities were determined at a test temperature of 40°C.

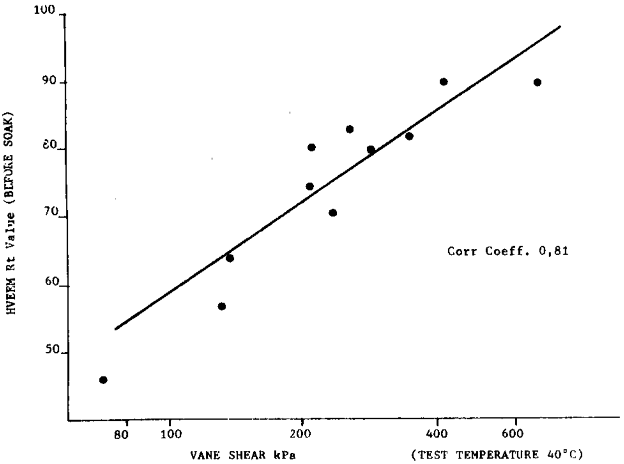

Fig. 1. Relationship between maximum laboratory vane shear strength and maximum Hveem Resistance Value

A good correlation (correlation coefficient 0,8) was found between maximum vane shear strength (log scale) and maximum Hveem Resistance Value (for both before and after soak conditions). As shown in Fig. 1, the minimum vane shear strength of 200 kPa at 40°C for a satisfactory performance proposed by Marais and Freeme[4] corresponded well with a minimum Hveem Resistance Value of 71 advised by the Asphalt Institute for bitumen emulsion base mixtures for light and medium traffic.[5] For heavy traffic the recommended Hveem Resistance Value of 78 corresponds to a vane shear strength of 270 kPa.

As vane shear criteria were originally derived for unsoaked conditions stability criteria used in this investigation are shown in Table I.

TABLE I

Stability criteria used in the Investigation

Traffic	Hveem Resistance Value after moisture vapour soak	Vane Shear Strength - kPa
Light and Medium DTN* under 100	71	200
For heavy and very heavy traffic DTN over 100	78	270

The benefit of duplicating shear tests, was the advantage that vane shear strength could be evaluated in the laboratory and in situ,[6] whilst Hveem tests could determine the effect of moisture vapour soak.

As indicated previously there was a poor correlation between gradation and shear strength and by utilising the above criteria it was not possible to develop a grading envelope that would ensure adequate stability. As shown in Tables I and II in Appendix 1, low stabilities were obtained for the particularly dirty or clean sands, and a filler content of between 5 and 14 percent should be considered as the main grading requirement.

3. MATERIALS CHARACTERISATION

Sands 5, 16, 17 and 18 were selected from the initial investigation for a more detailed study of the material characteristics and for an evaluation of the properties and performance in the field. A description of these sands is given in Table II.

TABLE II

Description of Sands Evaluated in the Laboratory and the Field

Reference	Description
Sand 5	Mine Dump Sand, West Rand, poorly graded, angular particle shape
Sand 16	Cape Flats Sand plus filler, poorly graded, rounded particle shape
Sand 17	West Rand River Sand, well graded, irregular particle shape
Sand 18	A 50/50 blend of Sands 5 and 17

Sands 5 and 16 were particularly poor quality materials, lacking little mechanical interlock due to either gradation or shape. Both sands are used in asphalt wearing course mixtures where additional stability or reduced void content is obtained by blending with other fine aggregate or using high stone content mixtures.

Sand 17 is a good quality fine aggregate that was used locally in gap-graded asphalt. The 50/50 blend of sands 5 and 17 having properties somewhere between the two extremes.

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* DTN - Design Traffic Number. The average daily number of 80KN single axle loads for the design lane during the design period.

3.1. Shear Strength

The effect of bitumen content on vane shear strength, Hveem Resistance Value and void content for sands 5 and 16 are shown in Fig. 2.

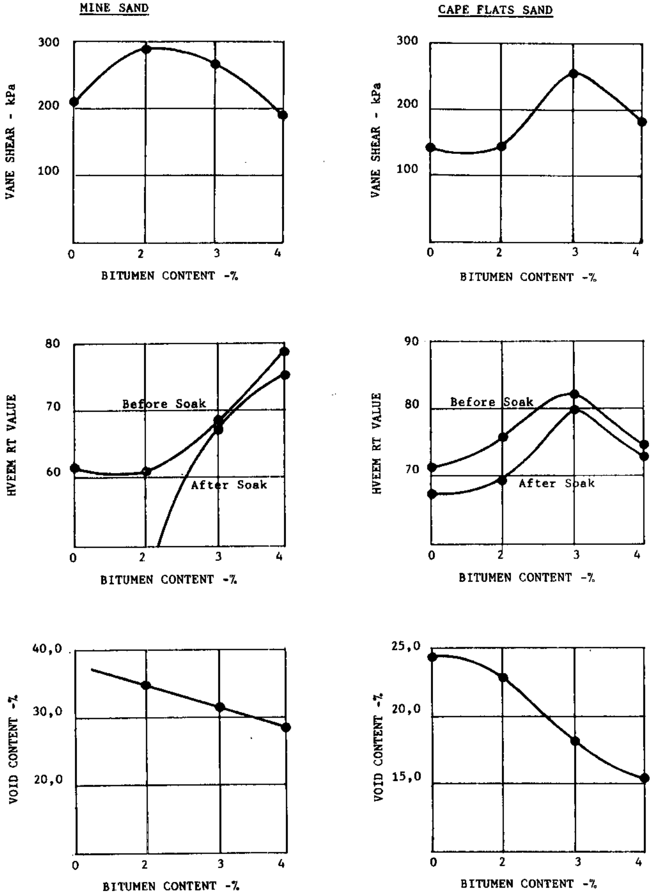

Fig. 2. The effect of bitumen content on vane shear strength, Hveem Resistance Value (Rt) and void content for Mine Dump and Cape Flats Sand. (TEST TEMPERATURE 40°C)

The effect of moisture vapour soak is illustrated for the stabilised Mine Dump Sand. Although vane shear strengths of the unsoaked samples are acceptable at bitumen contents of 3% and less, there is a rapid drop in shear strength for soaked samples, such that a minimum bitumen content of 4% would be required.

For the Cape Flats Sand mixtures both vane shear strength and Hveem Resistance Value peak at 3% bitumen content. Void contents are significantly lower than for the Mine Sand mixture, indicating the denser packing characteristics associated with a very rounded sand.[7]

The effect of blending the River Sand (Sand 17) with the Mine Dump Sand on both vane shear strength and Hveem Resistance Value is shown in Fig. 3. Vane shear strength and Hveem Resistance Value (before soak) increase significantly with increase in River Sand proportion. The addition of River Sand had little effect on the after soak stability.

The effect of temperature on vane shear strength is shown in Fig. 4.

Vane shear strength decreases with increase in test temperature. Similar curves for cutback tar and cutback bitumen mixtures have also been reported by Marais.[6]

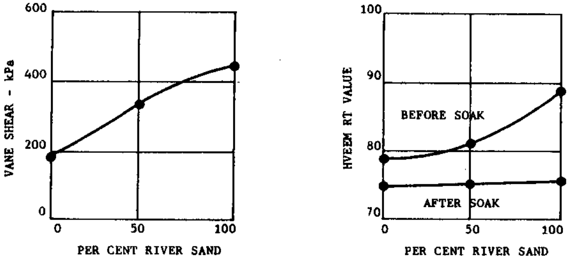

Fig. 3. The effect of blending River Sand with Mine Sand on vane shear strength and Hveem Resistance Value. (Bitumen content 4%, Test temperature 40°C)

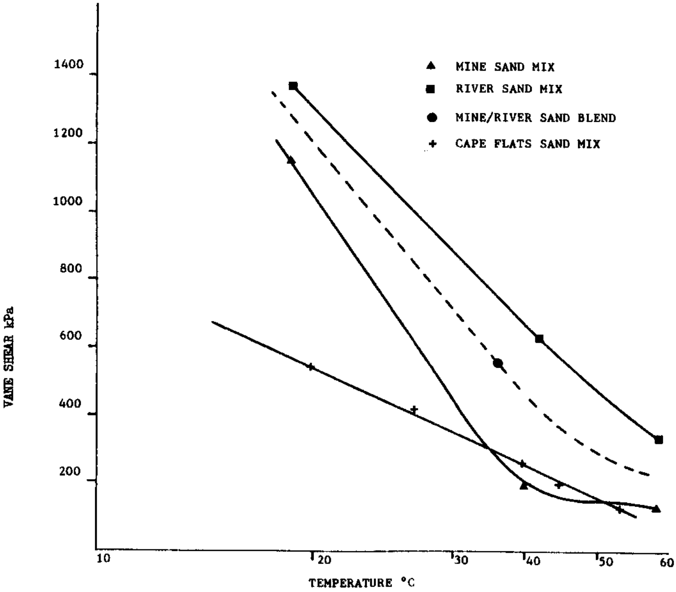

Fig. 4. Effect of temperature on vane shear strength

3.2. Dynamic Testing

The resilient moduli (MR) of the foam stabilised mixtures were measured using the repeated load indirect tensile procedure as described by Schmidt.[8] For this procedure a light 0,1 sec duration pulsing load was applied across the vertical diameter of the cylindrical specimen and the horizontal elastic deformation was measured by a pair of transducers. To determine the effect of load duration and stress level these measurements were supplemented with repeated load indirect tensile test measurements using an electrohydraulic testing machine capable of applying loads with durations between 0,05 and 1 sec and stress levels up to 600 kPa.

Using the procedure reported by Kennedy,[9] the resilient moduli were determined for the following foam stabilised sands:

Cape Flats Sand	3% bitumen content
Mine Sand	4% bitumen content
River Sand	4% bitumen content
50/50 Mine River Blend	4% bitumen content

In all cases the binder was a foamed 60/70 pen bitumen.

The effect of stress level and load duration on resilient moduli is shown in Figures 5 and 6. The resilient modulus of the foam treated sands decreased with increase in stress level and loading rate.

The effect of temperature on resilient moduli for constant load duration and stress level is shown in Figure 7.

These curves indicate that the resilient moduli of the sand stabilised mix would be optimised for pavement areas experiencing low stresses and fast moving traffic. Similar observations were also made by Walker and Hicks[10] on hot mix sand asphalts.

4. FULL SCALE EXPERIMENTS

To evaluate the shear strength and structural properties of mixtures stabilised with a foamed bitumen in the field the following mixtures were tested under full scale conditions:

A. The stabilisation of:- (a) Mine Dump Sand
(b) River Sand
and (c) 50/50 Blend of Mine/River Sand

with 4% foamed bitumen mixed in a conventional drum mixer.

B. The stabilisation of Cape Flats Sand plus blends of Cape Flats Sand and quarry overburden with 3% foamed bitumen mixed in situ using a pulvimixer.

4.1. Material Manufacture and Construction Behaviour

4.1.1. Drum Mix Plant Stabilisation

The foam stabilised sand sections form a 150mm base at an industrial plant near Krugersdorp. Approximately 1 000 tonnes of mix have been manufactured with 4% of 60/70 pen bitumen foamed to 15 times expansion and mixed in a 60 tonne/hour drum mix plant.

Excellent bitumen dispersion was achieved by directing the foam spray from the ten nozzles of the spray bar on to the curtain of sand falling from the conveyor into the drum. The mixed material was then hauled to site. tipped, graded and compacted in one 150mm layer by three passes of a steel wheel roller and fifteen passes of a pneumatic roller.

It is desirable to add sufficient water to the sand such that the addition of the foamed bitumen will result in an optimum fluid content. However, due to the heavy rains prior to the experiment, moisture contents of the River Sand and River/Mine blend were in excess of the moisture content required for maximum dry density.

Marais[6] found, on his studies of sand stabilised materials, that peak shear strength is usually on the dry side of the maximum dry density. At the higher moisture contents the mix has excess fluids and the drop in dry density will cause a decrease in shear strength.

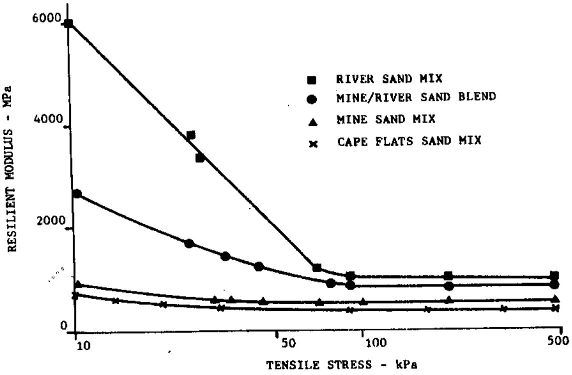

Fig. 5. Effect of stress level on resilient moduli (0,1 sec load rate)

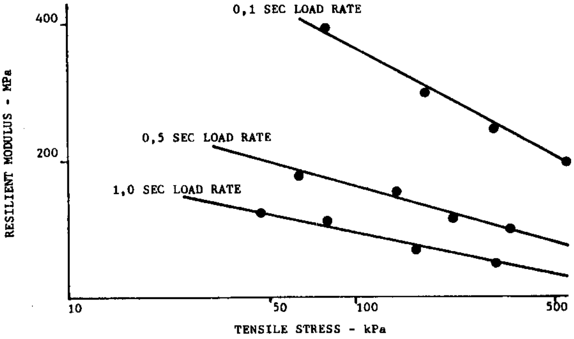

Fig. 6. Effect of stress level and loading rate on resilient moduli for Cape Flats Sand stabilised with 3% bitumen

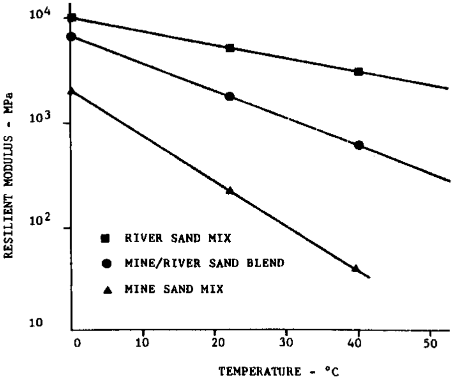

Fig. 7. Effect of temperature on resilient modulus (0,1 sec load rate, tensile stress 15 kPa)

A comparison between design laboratory vane shear at optimum moisture content and laboratory vane shear at the field moisture contents is shown in Table III.

TABLE III

Effect of compaction mositure content on Vane Shear Strength

Mix Type	Optimum m.c. %	Lab Vane Shear at o.m.c. kPa	Field m.c. %	Lab Vane Shear at Field m.c. kPa
River Sand + 4% b.c.	4,0	670	8,9	412
River/Mine + 4%	6,0	460	8,7	344
Mine	8,0	193	6,4	195

The importance of controlling the quantity of added compaction water to achieve maximum shear strength is further demonstrated in Figure 8 for the Mine Sand mix. At moisture contents greater than 8 percent there is a rapid decrease in Hveem Rt Value.

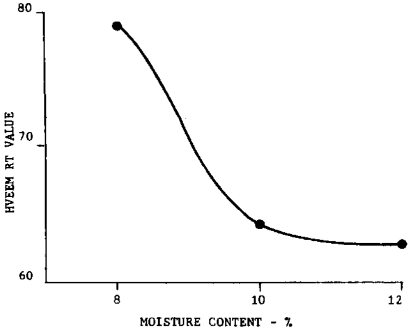

Fig. 8. The effect of added compaction water on Hveem Rt Value (before soak) for the Mine Sand mix. (Bitumen content 4% Test temperature 40°C)

Sand replacement densities of the three sections were between 98 and 104 percent of the dry density of material sampled from the field and compacted in a C.B.R. mould using Mod. AASHO compaction. Binder content was controlled by the setting of the variable speed bitumen pump and was in the range of 3,7 - 4,0% for all mixtures.

All mixtures handled well during construction and the drum mixer proved to be well suited for producing this type of material.

4.1.2. In situ stabilisation

The local Cape Flats Sand was watered, compacted and shaped to the required longitudinal and horizontal levels. The design filler content of 10 percent was obtained by mixing imported filler to a depth of 150mm by one pass of a rotovator. The sand layer was then recompacted and graded as previously described.

The field stabilisation train consisted of a tracked bulldozer, rotovator and bitumen tanker. The bulldozer was required to prevent traction problems in the sand and ensure a constant forward speed. The bitumen was not as well dispersed in the sand as for the drum mixed material. By varying spray rate and forward speed of the stabilisation train, bitumen distribution was noticeably improved and it was felt that good dispersion could be accomplished. Binder contents measured on the sand stabilised section varied between 2,3 and 4,0%, the higher values occurring where overlap of the mixing train took place.

After foaming, additional water was combined with the sand and sand/overburden blends to achieve optimum moisture content. The stabilised material was then graded and compacted with a vibratory and pneumatic roller. The sand stabilised section was particularly unstable under the wheels of the pneumatic roller. The facility for reworking the foam stabilised sand proved to be a distinct advantage when working with this initially unstable material.

A comparison between the shear strength of the laboratory stabilised Cape Flats Sand mix and field stabilised material, compacted and cured in the laboratory is shown in Table IV.

TABLE IV

Comparison between Shear Strengths of Laboratory prepared Samples and in situ mixed material

Mix Type	Vane Shear at 40°C kPa	Hveem Rt values at 40°C before soak	Hveem Rt values at 40°C after soak
Lab Prepared	255	84	80
Field mixed Cape Flats sand	206	80	65

As indicated above the poorer bitumen dispersion resulted in lower values of shear strength than for the laboratory mixed material. This is especially true for the after soak samples.

In addition to the stabilised sand section, three further sections of various blends of sand and quarry overburden were also stabilised in situ with 3% bitumen content. These experimental sections form 0,6 km of a road in Stellenbosch, Cape Province.

5. FIELD MEASUREMENTS

5.1. Shear Stability

5.1.1. Materials Stabilised in the Drum Mixer

(a) Field Vane Shear Strengths

As shown in Figure 9 there has been a significant increase in vane shear strength of all sections since construction. Vane shear strengths have been corrected to a standard temperature of 40°C using Fig. 4.

All stabilised sand sections were left unsurfaced during the first 9 months after construction and were subjected to the Highveld summer rains and site construction traffic for that period. Although these conditions have retarded the setting of the base layer, vane shear strengths indicate that apart from the Mine Sand mix, mixtures have met the minimum vane shear criterion of 200 kPa after 200 days, and that the stabilised material has reached the laboratory cured strength after 320 days.

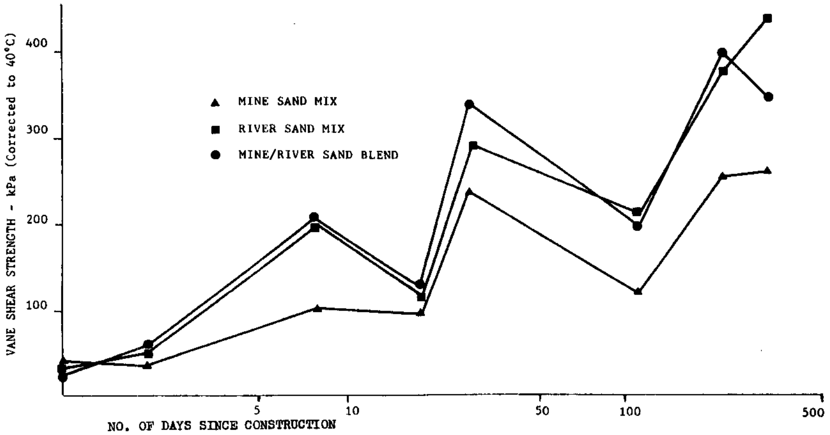

Fig. 9. Increase of vane shear strength with time. Plant mix 4% foamed bitumen

(b) Field Dynamic Cone Penetrometer Tests (D.C.P.)

As shown in Figure 10, mean penetration/blow value reduced with number of days since construction.

The Dynamic Cone Penetrometer as developed by Van Vuuren[11] has not, to the writer's knowledge, been used for the evaluation of bitumen stabilised sand layers. Hence there are no established criteria in terms of penetration/blow for such materials. Using the relationship between D.C.P. and CBR value, CBR's for the stabilised Mine, River and Mine/River blends are 45, 93 and 80 respectively 220 days after construction.

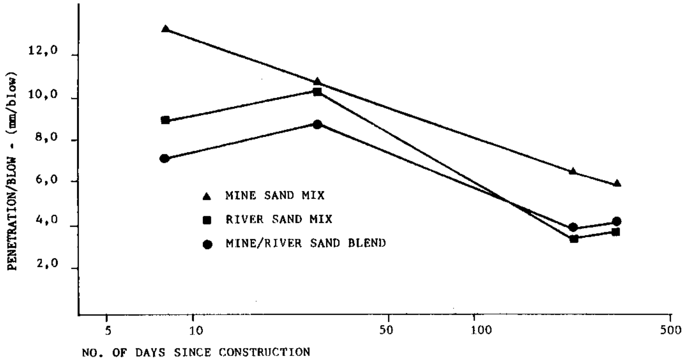

Fig. 10. Increase of Dynamic Cone Penetrometer value with time. Plant mix 4% foamed bitumen.

5.1.2. Materials Stabilised In Situ

(a) Field Vane Shear Strengths

The increase in field vane shear strengths with time is shown for the Cape Flats Sand and sand overburden blends in Figure 11. Vane shear strengths of the sand/overburden blends are included in the graph but were not measured in the laboratory due to the interaction between the vane, coarse stone and edge of the CBR mould. The laboratory vane shear strength of the cured sand mix was reached on the road after 165 days, during this period there was a five fold increase in measured field values.

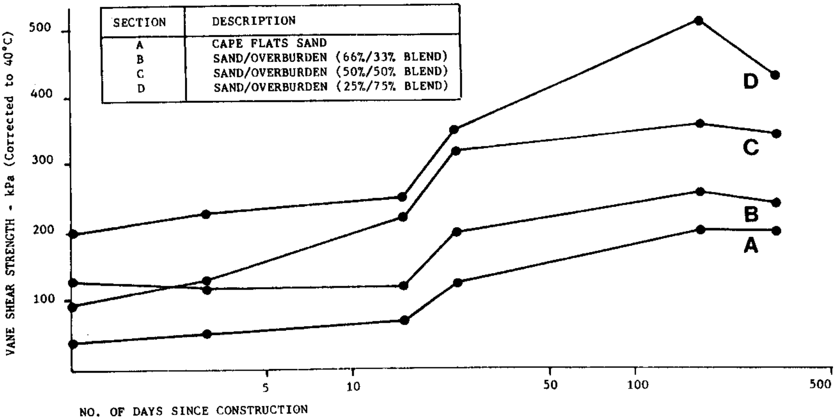

Fig. 11. Increase of vane shear strength with time. In situ mixing 3% foamed 60/70 pen bitumen.

(b) Field Dynamic Cone Penetrometer Tests (D.C.P.)

Decrease of penetration/blow with time for the sand and sand/overburden blends are shown in Figure 12. Although the Cape Flats sand mix was particularly unstable both during and immediately after construction D.C.P. values of all experimental sections have converged to a value between 3,5 and 7,0mm/blow after 165 days.

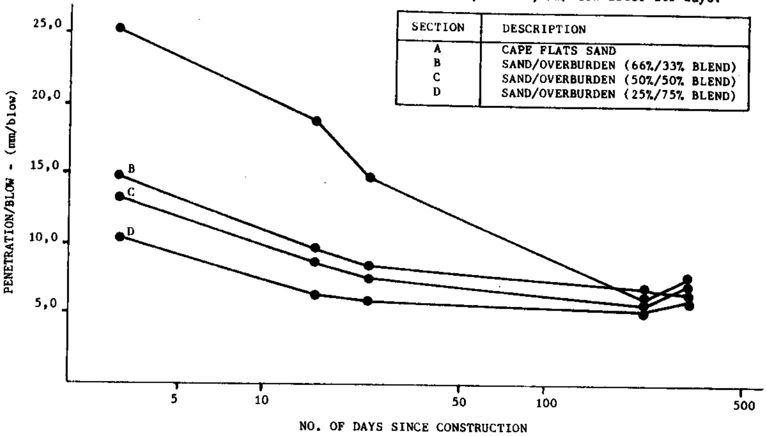

Fig. 12. Increase of Dynamic Cone Penetrometer value with time. In situ mixing 3% foamed 60/70 pen.

6. STRUCTURAL ANALYSIS

As shown in Section 3.2, resilient moduli of the stabilised sand mixtures were dependent on loading rate, stress level and temperature, moduli increasing with thickness of cover and depth within the layer.

Main possible forms of distress of the 150mm thick layer were thought to be deformation due to either shear in the stabilised layer or deformation in the subgrade.

The design aim was therefore to add sufficient binder to achieve the stability requirements (Hveem Rt Value, vane shear) and by using linear elastic theory the stabilised layer thickness was selected to produce acceptable vertical strains in the subgrade for the known traffic level.

Representative values of the resilient modulus for each of the experimental sections were derived from:-

1. the laboratory values of resilient modulus at high stress levels and load duration of 0,1 sec.
2. the measured surface deflection and curvature and relating to the moduli of the base and subgrade layer. (See Appendix 2).
3. the relationship suggested by Heukelom and Klomp[12] for subgrade soils.
   Emod = C.B.R. x k (where C.B.R. values were derived using the Dynamic Cone Penetrometer and factor k was taken as 10).

The elastic moduli of all five mixtures using the above methods are shown in Table VI.

TABLE VI

	Laboratory[1] Modulus - MPa	Modulus[2] derived from Deflection and Curvature - MPa	Modulus[3] using CBR relationship
River	1000	-	800
River/Mine	850	-	800
Mine	500		480
Cape Flats sand	360	380	450
Sand/overburden	600	390	480

From Benkelman Beam deflection and Hveem Rt value measurements the moduli of the subgrade material for both experiments were computed to be between 125 - 130 MPa. A value of 130 MPa was chosen for the analysis.

The effect of base modulus and thickness on vertical compressive strain in the subgrade for a 40 kN single wheel load is shown in Figure 13.

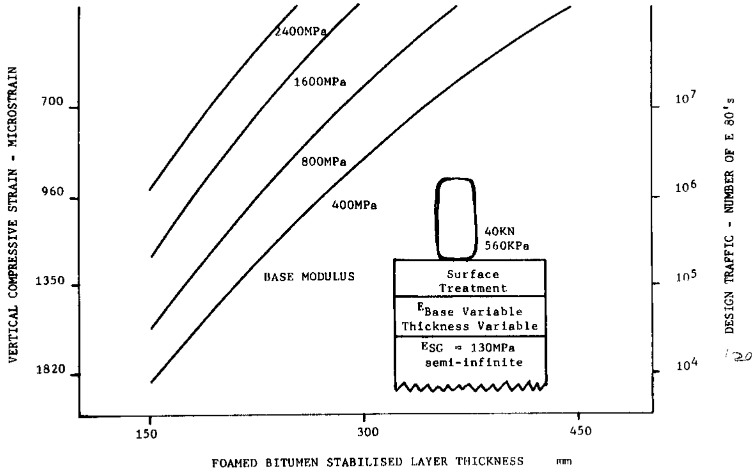

Fig. 13. The effects of base modulus and thickness on vertical compressive strain in the subgrade for constant subgrade modulus of 130 MPa, surface treatment and wheel load of 40 KN. (Category C Road)

Vertical compressive strain criteria used to limit subgrade deformation are those proposed by Paterson [13, 14] for a category C road (terminal riding quality (PSI) of 1,5, terminal rut depth of 20mm for more than 20% of road length).

Predicted traffic to cause excessive subgrade deformation for the structural designs used in the two experiments range from approximately 10 000 E80's for the Cape Flats Sand mixture to 100 000 E80's for the River Sand mix, the number of repetitions increasing rapidly with increase in thickness and base modulus.

The above example is clearly a simplified analysis. In particular it was thought that the indirect tensile method of measuring the moduli could not completely characterise the stress dependency of the sand stabilised mixtures; hence vertical sublayering of the non-linear layer was not attempted.

7. CONCLUSIONS

The shear strengths of a wide range of foam stabilised sands were evaluated in the laboratory, the main sand properties influencing shear strength being sand shape and filler content. Low stabilities were obtained for particularly dirty and clean sands, and a filler content of between 5 and 14 percent should be considered as a grading requirement. A good correlation was found between maximum Hveem Rt Value and maximum vane shear strength. The Rt Value of 71 for emulsion stabilised base mixtures advised by the Asphalt Institute[5] compared well with the minimum vane shear strength of 200 kPa proposed by Marais and Freeme.[6]

Full scale experiments were constructed with sand stabilised in a drum mix plant and stabilised in situ. Bitumen dispersion was considerably better for the central mix plants than for the sand stabilised in situ. By varying spray rate and forward speed of the stabilisation train, bitumen distribution was noticeably improved and it was felt that good dispersion could be accomplished. All stabilised sections showed significant increases in shear strength with time and full laboratory design strength was reached in the field 6 - 10 months after construction.

Resilient moduli of the foam treated sand mixtures were determined using the repeated load indirect tensile test procedure. Moduli were found to increase with increase in loading rate and decrease of stress and temperature.

By determining the effective modulus for the foam treated sand layer from both the laboratory and field measurements a structural design analysis was carried out to determine the required layer thickness for a given traffic level and wheel load.

ACKNOWLEDGEMENTS

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Appendix 1

TABLE I

Maximum Hveem Rt Values (before and after soak) and Maximum Vane Shear Strengths

Sand Reference	Description	Max. Hveem Before MVS	Max. Hveem After MVS	Max Vane Shear strength kPa
1	Richards Bay Sand	72 (3%)	54 (3%)	-
2	Durban River Sand	93 (0%)	69 (4%)	-
3	Durban River Sand + 10% F. Ash	86 (0%)	61 (0%)	-
4	Durban River Sand + 20% F. Ash	85 (0%)	69 (0%)	-
5	Mine Sand (Chamdor)	79 (4%)	75 (4%)	283 (2%)
6	Cape Vidal Sand	70 (4%)	66 (4%)	231 (0%)
7	Durban Sand	64 (0%)	63 (5%)	136 (2%)
8	Wilderness Sand	74 (3,5%)	65 (3,5%)	206 (3,5%)
9	Umdloti Sand	89 (2%)	83 (2%)	689 (2%)
10	Silverton Sand	110 (2%)	101 (2%)	-
11	Saldanha Sand	95 (2%)	90,5 (4,5%)	-
12	Cape Flats Sand	57 (3,5%)	57 (3,5%)	140 (2,5%)
13	Cape Flats Sand + 3% Filler	63 (3%)	65 (4%)	-
14	Cape Flats Sand + 5% Filler	61 (3%)	66 (4%)	-
15	Cape Flats Sand + 7% Filler	58 (3%)	57 (4%)	-
16	Cape Flats Sand + 10% Filler	82 (3%)	80 (3%)	255 (3%)
17	Chamdor River	89 (4%)	75 (4%)	412 (4%)
18	Chamdor (River + Mine)	81 (4%)	74 (4%)	344 (4%)
19	Cape Flats Sand (Field)	80 (3,0%)	65 (3,0%)	206 (3,0%)
20	Port Elizabeth Sand	46 (3,5%)	46 (3,5%)	75 (3,5%)

Value in bracket corresponds to mix binder content

Test Temperature 40°C

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Appendix 1

TABLE II

Wet Gradings of Sands Evaluated in the Investigation

Sand Reference	Cumulative Percent Passing-Sieve Size mm							Accept/Reject for medium traffic
	4,75	2,36	1,18	0,600	0,300	0,150	0,075	
1	100	100	99,7	94,9	65,5	13,5	4,7	Reject
2	99,1	98,8	98,0	93,1	58,5	21,0	7,9	Reject
3	99,8	99,4	98,5	94,1	64,2	29,2	14,5	Reject
4	99,8	99,6	98,7	94,9	69,2	36,8	20,4	Reject
5	100	100	100	96,0	62,0	31,0	13,5	Accept
6	100	100	100	100	84,0	5,0	2,0	Reject
7	100	100	100	99,0	66,0	11,0	2,0	Reject
8	100	100	100	100	71,0	25,0	0	Reject
9	100	100	100	100	92,0	39,0	13,0	Accept
10	100	99,1	98,0	85,8	51,9	19,2	7,0	Accept
11	97,0	95,0	92,0	85,0	66,0	31,0	9,6	Accept
12	100	100	99,5	98,0	67,0	20,0	0	Reject
13	100	100	97,5	95,0	66,0	20,0	5,2	Reject
14	100	100	98,5	97,0	67,0	21,5	7,2	Reject
15	100	100	99,5	99,0	68,5	23,0	9,2	Reject
16	100	100	99,5	98,0	79,0	23,0	10,0	Accept
17	97,0	83,0	49,0	27,0	16,0	10,0	6,5	Accept
18	99,0	93,0	75,0	56,0	36,0	21,0	10,0	Accept
19	100	100	99,5	98,0	79,0	23,0	10,0	Reject
20	100	100	99,6	98,6	90,6	43,6	9,2	Accept
21	100	100	100	100	99	5	0	Reject

Appendix 2

Using the method proposed by Grant and Walker[1] the in situ moduli of the subgrade and stabilised base layer were determined by employing measurements of surface deflection and radius of curvature. Curves later developed by Grant[2] relating computed values of deflection and curvature to subgrade modulus and base subgrade modular ratio for a Benkelman beam truck wheel load and configuration are shown in Figure 1.

Mean values of measured Benkelman beam deflection and radius of curvature for both experiments are shown in Table I.

TABLE I

Field deflection and radius of curvature measurements

Material Description	Deflection - mm	Curvature - m
In situ Experiment after 165 days		
Cape Flats sand mix	0,53	64,7
Sand/overburden	0,51	67,6
Sand Subgrade	-	-
Central Mix Experiment		
Selected subgrade	0,53	55,0

From Figure 1 the effective moduli for subgrade and basecourse layers were as follows:-

In situ experiment

Selected Subgrade	125 MPa
Cape Flats Sand Mix	188 MPa
Sand/Overburden Mix	195 MPa

Central Mix Experiment

Selected Subgrade	130 MPa

As previously discussed the moduli of the sand stabilised mix were dependent on rate of loading. It is estimated that the forward speed of the Benkelman Beam Truck would correspond to a loading rate between 0,5 and 1,0 sec.

The derived values of moduli were therefore adjusted to the faster loading rate of 0,1 sec using Figure 6 in the main text.

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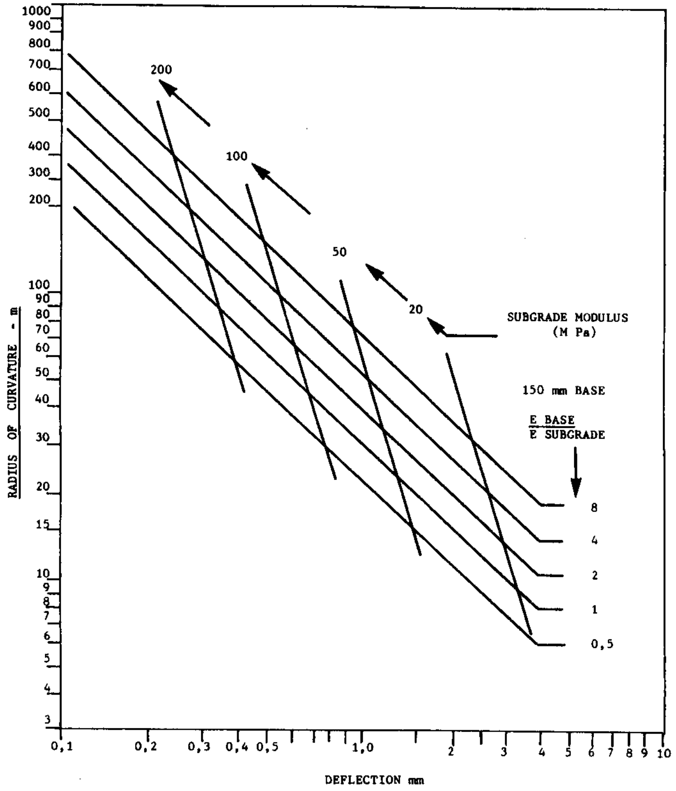

Fig. 1. Relationship between deflection, radius of curvature, and modulus of subgrade for pavement with 150mm thick base and surface treatment